

GRID BALANCING WITH A LARGE-SCALE ELECTROLYSER PROVIDING PRIMARY RESERVE

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Abstract

As the share of renewable energy sources increases, the grid frequency becomes more unstable. Therefore, grid balancing services will become more important in the future. Dedicated devices can be installed close to the point where off-shore wind farms are connected to the transmission grid on land. There, it can be used to attenuate power variations, reduce congestion and offer grid balancing. These ancillary services can create significant economic revenue.

In this paper, the provision of the primary reserve by means of a large hydrogen electrolyser of 25 MW is investigated for the specific case of the Belgian transmission system. The electrolyser is used to convert water and excess power to hydrogen gas, which is injected into the natural gas grid. The revenue for primary reserve (R1) provision is analysed on a techno-economic model, including capital costs, operational costs, the revenue of the generated hydrogen and oxygen products and the ancillary service income. The revenue depends strongly on the contracted power-band. Therefore, it is optimised to yield maximum revenue. The results show that providing R1 creates a considerable revenue. Therefore, a large electrolyser can be a good candidate to buffer excess renewable energy into green gas while simultaneously providing grid support.

1 Introduction

The electric power industry is changing continuously due to a growing diversity in the energy mix. This is mainly caused by the increasing share of renewable energy sources. Global warming and climate change are the main reasons for a rapid global transition towards renewable energy generation. Furthermore, fossil fuel reserves are being depleted progressively while the demand for energy keeps increasing. Clearly, a more diverse energy mix is needed, which requires a change in the structure and operation of the conventional power system.

Besides the positive aspects of increasing the share of renewables in the energy mix, the technical feasibility of integrating variable renewable sources should be considered. Due to the intermittent nature of these sources, they bring more

fluctuations and uncertainty into the grid and complicate its operational management. However, as wind and solar power are the fastest growing sources of electricity, their effects must be taken into account. For example, the inertial response of the grid on power imbalances is determined by all rotating masses of the turbo-generators in the system. However, renewable power sources such as wind turbines and photovoltaics do not possess rotating inertia directly coupled to the grid, which reduces the robustness and reliability of the power system [1- 3].

Different solutions such as energy storage systems, demand-side response and curtailment of variable renewable energy sources have been suggested to manage the energy flows and increase the flexibility of the grid [4-6]. Hydrogen storage, as an energy carrier with a high capacity and fast discharge time, can be one of the possible options to support the grid [7,8]. Classically, direct conversion of electrical energy to hydrogen is not economically viable. However, large scale electrolysers as an energy-intensive technology can be operated to support the grid by adjusting the input power according to the grid frequency variation, i.e., to deliver ancillary services.

In this paper, a techno-economic analysis is performed of a 25 MW electrolyser installation in Belgium. A numerical model is developed in Matlab to assess the economic benefits of running a 25 MW electrolyser with two different strategies. In the first strategy, the power consumption is varied based on the electricity price variations on the Belpex market. In the second strategy, the economic return is maximised by providing primary reserve (R1) as an ancillary service.

2 Methodology

2.1. Business case description

Since hydrogen production through electrolysis is an energy-intensive process, the electricity price is of vital importance to the economic viability of the electrolyser. As the first business case, the electrolyser is operated to follow the variations in the electricity price to maximise the economic return. Transmission grid costs are not taken into account, as it is assumed that the electrolyser is installed on the site of a renewable energy source, e.g., a wind farm. Hydrogen storage

is not foreseen in the model, assuming that all the produced hydrogen can be injected into the conventional natural gas grid as long as a limit of 2% volume hydrogen is not exceeded. To inject the hydrogen into the existing natural gas pipeline, it must be compressed from 30 to 70 bar. It is assumed that the compression stages are not costly, i.e., the compression station costs are not included in the model. However, for high-pressure applications such as mobility (pressure level of 700 bar), the compression cost is not negligible. For a system connected to a 36 kV voltage level with more than 70 GWh of yearly energy consumption. Injecting hydrogen in the natural gas grid reduces the CO₂ emission about 202 kg/MWh (39 kWh_{HHV}/kg_{H₂}) [9]. Table 1 gives an overview of the assumptions and the main parameters of the electrolyser.

Table 1. 25 MW electrolyser parameters and assumptions

25 MW PEM Electrolyser	
Capital expenditure (CAPEX)	1000 (€/kW) [9]
Operational cost	1% of capital cost
H ₂ output	5000 (Nm ³ /h)
Lifetime	20 (years)
Availability	98%
Cell stack lifetime	80000 (hours)
Operating hours	8760 (hours/year)
Substitution cell	50% of capital cost
Output pressure	30 (bar)
Hydrogen production efficiency	100% [9]
Connection cost to the power grid	500.000 (€)
Connection cost to the gas grid	2.250.000 (€)
Value of generated hydrogen	2.2 (€/kg) [9]
Value of generated oxygen	24.5 (€/ton) [10]

The second business case aims to analyse the possible profitability of using the electrolyser system to provide demand-side response (DSR) services. Ancillary services are essential to support the power grid stability in unbalanced situations. Moreover, participating in the ancillary market brings additional economic revenue. The ancillary services can be provided by regulating the power offtake of the electrolyser according to the grid frequency. In this economic model, the power consumption profile of the electrolyser is built based on the frequency variation of the grid in 2017 in the Belgian grid, operated by the Transmission System Operator (TSO) ELIA.

The additional economic revenue of the provision of each primary reserve product (2 symmetrical and 2 asymmetrical products) will be investigated. Symmetrical R1 products are delivered within a frequency deviation of 100 or 200 mHz from the nominal one (50 Hz), and asymmetrical R1 products are provided if the frequency deviates more than 100 mHz. The power reserve offered by the electrolyser is assumed to be constant for the whole year, though the tendering process is evolving to a shorter period in the future.

The power response of alkaline and Polymer Electrolyte Membrane (PEM) electrolysers to frequency variations of the grid can be easily modulated. The response time from pressurized standby to a full-load operating condition is less

than three seconds. A hot-start is even faster, i.e., less than one second. However, it is not recommended to frequently switch the electrolysers entirely on and off in stand-alone systems, from a system frequency control perspective [11]. Therefore, to provide an adequate response to the grid frequency variation and to full fill the technical aspects, the electrolyser is supposed to be continuously operated in a variable way to avoid the start-up and shut-down time required to purge the nitrogen. Thus, a minimum operating capacity of 10% (2.5 MW) is considered.

The average prices of all primary reserve products in 2017 are given in Table 2. The electricity price in the model is equal to the average Belpex electricity price in 2017 (44.6 €/MWh). The same assumptions as the first business case are considered with a difference that the ancillary service is included in the optimization algorithm as an end product. Therefore, the algorithm maximises the annual cash flow of producing hydrogen and providing ancillary services as the end products, based on the annual average Belpex electricity price. The optimisation aims to optimize the baseload power and power reserve at which the maximum revenue is generated.

Table 2. Annual average price of contracted primary reserves

R1 product	Price (€ / MW/h)
100mHz	33
200mHz	15
Asymmetrical	4

2.2. Power input optimisation

In the first strategy, the power input of the electrolyser is dynamically modulated to follow the electricity price. No ancillary service provision is considered. The electric power consumption (P_e) is regulated as a linear function of the electricity price:

$$P_e = P_0 - K \cdot Price \quad (1)$$

Where K is a constant control factor that determines how strongly the power consumption reacts to price variations. The hourly electricity price is represented by the variable $Price$. P_0 is the baseload power which can be set between a minimum of 2.5 MW, to avoid start-up time, and a maximum of 25 MW. The optimization algorithm maximizes the annual Cash Flow (CF) of the system with an objective function in which electricity expenditure and hydrogen sale are respectively considered as the main cost and revenue drivers. The objective function of the algorithm is defined as follows:

$$CF = H_{2_{value}} \cdot H_{2_{produced}} - P_e \cdot Price \quad (2)$$

The amount of hydrogen produced varies on an hourly basis, as the electricity price also varies hour-by-hour. It is assumed that the hydrogen production is ideally proportional to the power consumption. The specific volume of hydrogen is calculated in normal conditions with a compressibility factor

of 1 bar [12]. Therefore, the specific volume of hydrogen (2.016 kg/kMol) is equal to 11.72 (m³/kg) at a temperature of 15°C and a pressure of 1 bar. The amount of produced hydrogen is thus calculated as:

$$H_{2\text{produced}} = \frac{200 \cdot P_e}{11.72} \quad (3)$$

Fig. 1 and Fig. 2 show the annual cash flow of the electrolyser as a function of the reference power (P_0) and the control parameter K . The annual cash flow reaches its maximum (351.5 k€) at $K = 0.35$ and $P_e = 25$ MW (maximum baseload). Operating the electrolyser at these optimum values generates the maximum revenue for the system, considering the hydrogen production and the electricity expenditure as the main parameters in the cost function.

Operating the electrolyser at its maximum capacity with $K = 0.35$ makes the cash flow mostly positive, giving the possibility to follow the electricity price with considerable hydrogen production. As a result, 1330 ton of hydrogen is produced yearly (15.561 millions of Nm³/kg) with an hourly average production of 161.8 kg/h (1893 Nm³/h and about 5 MWh LHV).

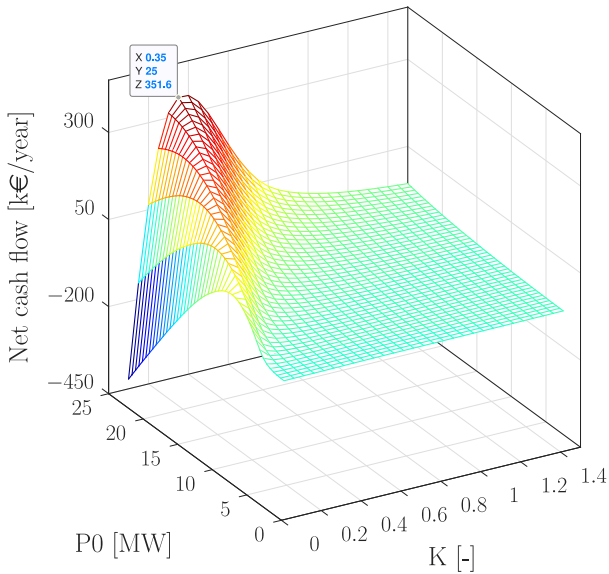


Fig. 1: Net cash flow as a function of K and P_0

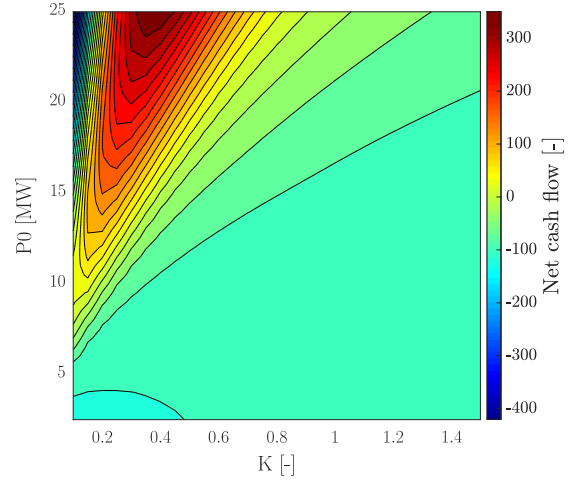


Fig. 2: Net cash flow contour plot

As illustrated in Fig. 3, the electrolyser power consumption follows the electricity price variations. Therefore, in the coldest months of the year (Jan., Sep., Oct., Nov., Dec.), when electricity prices are high, the power input is accordingly reduced to its minimum, and less hydrogen is produced. In contrast, in warmer months of the year, the electricity price and consequently the hydrogen production rise due to the low electricity price.

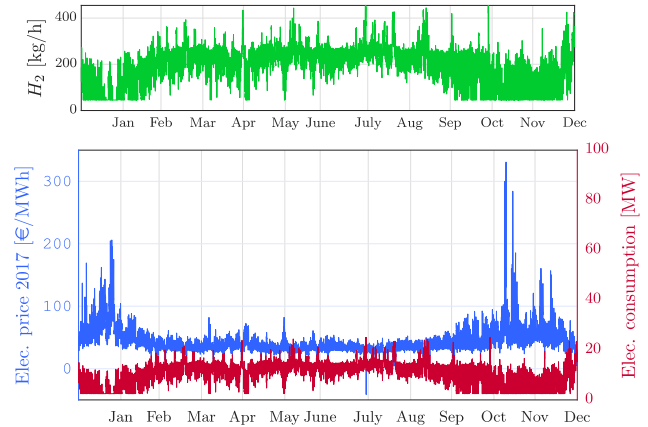


Fig. 3: Electrolyser power consumption in one year

Fig. 4 and Fig. 5 respectively give a detail of the power consumption, electricity price, and produced hydrogen in the whole month of January and the first day of the year. As can be seen, the electrolyser power consumption is scheduled based on the electricity price. This dynamical operation of the electrolyser maximises the cash flow as the cost function.

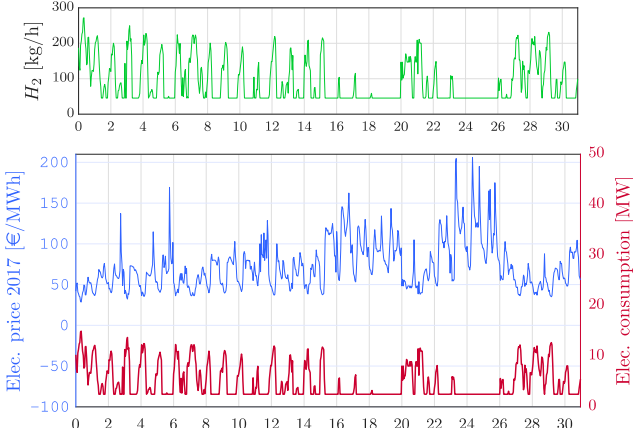


Fig. 4: Electrolyser power consumption in January

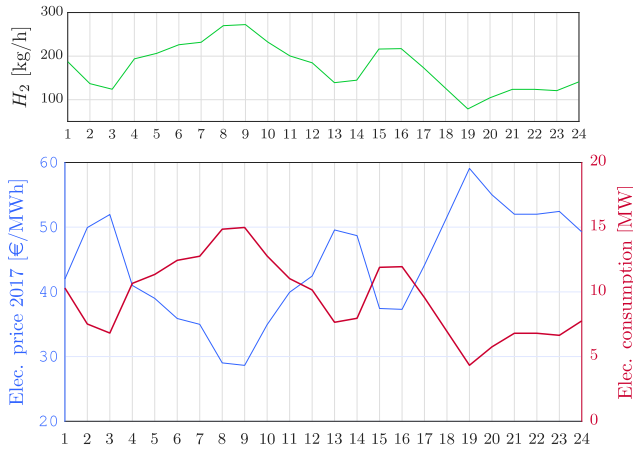


Fig. 5: Electrolyser power input in first day of the year

The results show that the electrolyser is only operated at the reference power ($P_0=25$ MW) on moments with a very low electricity price, particularly when the price becomes negative. As shown in Fig. 6, the electrolyser runs up to 25 MW on the 30th of July due to the negative electricity price.

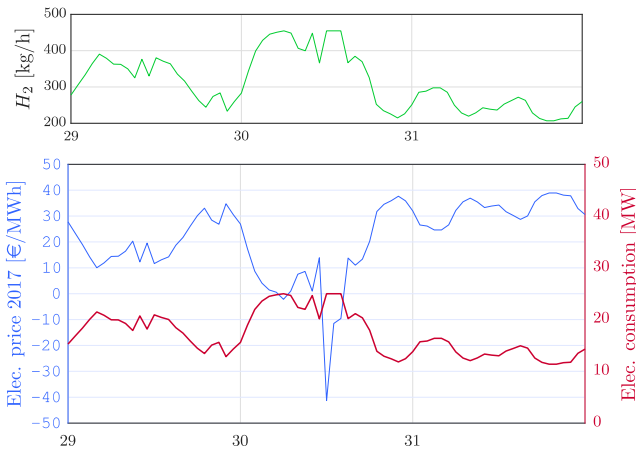


Fig. 6: Electrolyser power consumption in July

The investment profitability of the electrolyser for the lifespan of 20 years is calculated, taking into account both the operational and investment costs. The cash flow is kept identical for each year based on the assumption that both the hydrogen and electricity price will increase by the same amount. According to [9], the hydrogen value for on-site production will reach 2.72 €/Kg in 2030 and 3.59 €/Kg in 2050, with a average yearly increase of 2%. As the electricity prices are also expected to rise in the near future, an annual increase of 2% is assumed. However, by scheduling the power input according to the electricity price, the power consumption decreases, and the influence of the electricity price evolution is canceled out. The electrolytic cells wear out over time, and a replacement is required after 10 years (half of the lifetime) with a cost of 50% of the initial investment. This replacement cost is included in the cash flow of the 10th year, and it is weighed with the discounting factor. To analyse the economic feasibility of operating the electrolyser with the first strategy, the Net Present Value (NPV) is calculated as:

$$NPV = \sum_{k=1}^N \frac{CF(a)}{(1+i)^k} \quad (4)$$

Where a is the year, $CF(a)$ is the cash flow in the year a , i is the discount rate, and N is the lifetime. A discount rate of 2% is considered. As a result, despite the positive net cash flow, the calculated NPV is equal to a negative -31.82 M€ with a negative Internal Rate of Return (IRR) of -18%.

2.3. Providing primary reserve

2.3.1. Symmetric 100 mHz RI product: To provide a symmetrical 100 mHz product, the electrolyser is never operated at the maximum or minimum capacity on average, to keep the power reserve available for the positive and negative variation of the grid frequency. Therefore, the baseload power is set between 15% and 95% of maximum capacity (3.75 MW to 23.75 MW). In this strategy, the power input responds linearly and proportionally to the frequency variations of the grid. According to the grid operator regulations in Belgium, a deadband of 10 mHz (50 Hz \pm 10 mHz) is considered, in which the primary control is not allowed to react, and the electrolyser operates at its baseload power. The equation used to guarantee such behaviour is:

$$f(x) = \begin{cases} P_{el} = x \cdot P_{max} & -0.01 \leq \delta \leq 0.01 \\ P_{el} = x \cdot P_{max} + \delta \cdot K & \text{Otherwise} \end{cases} \quad (5)$$

Where x is the baseload power as a percentage of the maximum capacity (P_{max}). This is the variable that has been optimised in the algorithm. The frequency of the grid is represented by $Freq$. The parameter δ is the frequency deviation from 50 Hz ($\delta = Freq - 50$). K is the power-frequency characteristic of the electrolyser, defined as:

$$K = \frac{\Delta P}{\Delta f} \quad (6)$$

This primary reserve product covers the frequency variation up to 100 mHz ($\Delta f = 0.1$ Hz). The symmetrical product with respect to the nominal frequency gives an equal chance for downward and upward requests to stabilise the frequency. The equation that expresses the power reserve is as follows:

$$f(x) = \begin{cases} \Delta P = P_{el_{nom}} - P_{el_{min}} & x \leq \frac{1 - Min}{2} + Min \\ \Delta P = P_{el_{max}} - P_{el_{nom}} & x > \frac{1 - Min}{2} + Min \end{cases} \quad (7)$$

The annual cash flow is calculated as:

$$CF = H_{2_v} \cdot H_{2_p} + \Delta P \cdot R1 \cdot 8760 \cdot avail - P_e \cdot Price \quad (8)$$

Where $R1$ is the income from the primary reserve, H_{2_v} is the value of hydrogen (2.2 €/kg), $avail$ is the availability of hydrogen which is equal to 98%. H_{2_p} is the produced hydrogen which changes linearly with the power input indicated by P_e , and can be calculated using (3). The power-frequency chart of the R1 product is shown in Fig. 7. The power input follows the frequency variation with the optimum baseload of 13.75 MW. As shown, the primary reserve does not react within the first 10 mHz deviations from 50 Hz. As illustrated in Fig. 11, offering the 100 mHz product as the primary reserve and operating the electrolyser at 55% of its capacity, maximises the annual cash flow with a yearly income of 3.2 M€ by providing ancillary services. The profitability of the investment is estimated, considering a lifespan of 20 years. The NPV is equal to 8.12 M€ with a discount rate of 2%. The IRR is 4.8%, and the payback time is equal to 3 years.

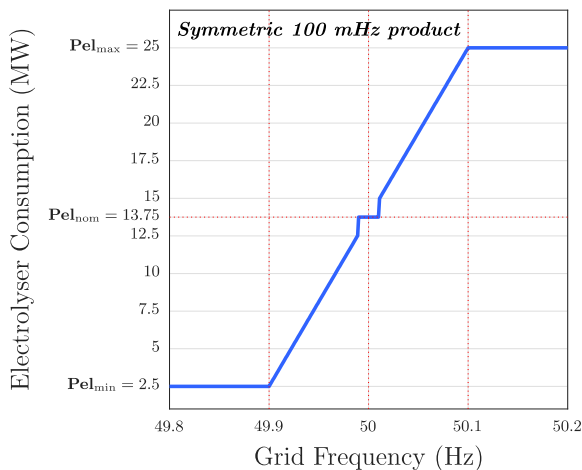


Fig. 7: Power-Frequency chart in the optimal technical condition for 100 mHz product

2.3.2. *Symmetric 200 mHz R1 product:* To provide a symmetrical 200 mHz product, the system reacts to a frequency deviation of 200 mHz from the nominal value. The power input reacts linearly to the frequency variation with a lower slope compared to the 100 mHz product, because of the less restrictive activation range (48.8 to 50.2 Hz). This is shown in the power-frequency chart (Fig. 8). As illustrated in Fig. 11, the maximum annual cash flow is achieved for the electrolyser operating at 55% baseload and providing 11.25 MW power reserve. Operating the electrolyser at its optimum baseload generates an income of 1.45 M€ from providing primary reserve and 4.63 M€ from the hydrogen production (in contrast to 4.5 M€ for the 100 mHz product). The profitability of the investment is investigated with the same method and hypothesis. The NPV is equal to -20.33 M€ with a discount rate of 2%. The IRR is equal to -7.6%.

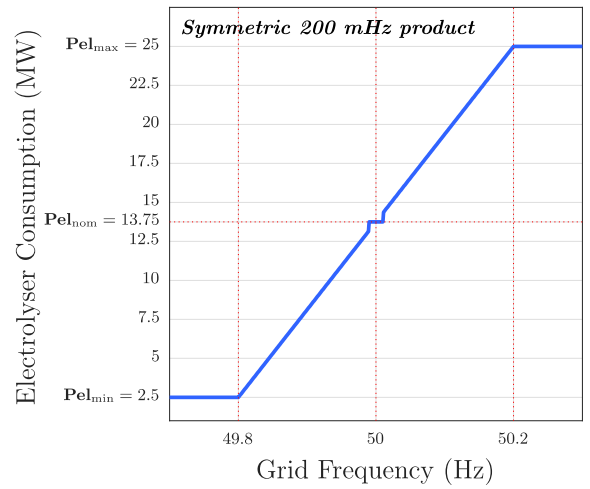


Fig. 8: Power-Frequency chart in the optimal technical condition for 200 mHz product

The dynamic response of the electrolyser delivering the symmetrical 100 mHz and the 200 mHz products is represented in Fig 12. The power input variation of the electrolyser providing the 100 mHz product is twice as high compared to the 200 mHz product. This is because of the fact that the system reacts to the frequency deviation within a different frequency range but with the same available power reserve.

2.3.3. *Asymmetrical R1 downwards:* To provide the asymmetrical product R1 downwards, the system reacts to frequency deviations above 50.1 Hz (positive frequency deviations). Therefore, if the grid frequency is above 50.1 Hz the power input of electrolyser follows the frequency as:

$$f(x) = \begin{cases} P_{el} = x \cdot P_{max} + \delta \cdot K & \delta > 0 \\ P_{el} = x \cdot P_{max} & \text{Otherwise} \end{cases} \quad (9)$$

Where $\delta = Freq - 50.1$, and K is the power frequency characteristic of the electrolyser for a frequency deviation of 0.2 Hz. To keep the power reserve available, the electrolyser cannot be operated at its maximum capacity. Therefore, the

baseload varies between a technical minimum of 10% and 95%. The power reserve is given by:

$$\Delta P = P_{el_{max}} - P_{el_{nom}} \quad (10)$$

As illustrated in Fig. 11, the maximum net cash flow of 674 k€/y is obtained by running the electrolyser at the minimum technical capacity as a baseload and providing 22.25 MW of power reserve. The power-frequency of the electrolyser operating at its optimum point is presented in Fig. 9. The optimal economic solution yields an income of 775 k€/y from offering primary reserve and 859 k€/y from the hydrogen sale. The economic feasibility of the R1 down product is investigated. Thus, the NPV is equal to -29.81 M€, and the IRR is -16%.

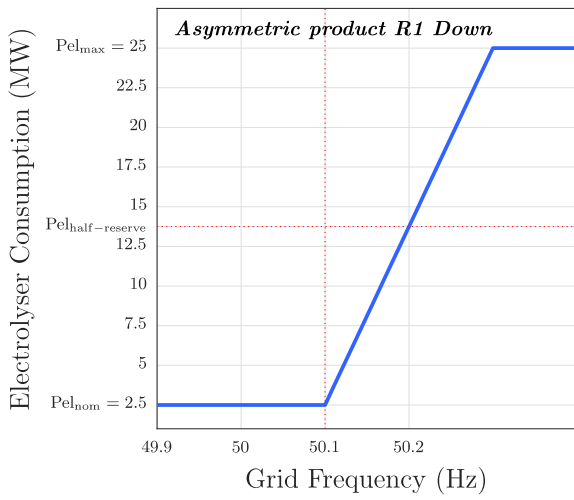


Fig. 9: Power-Frequency chart in the optimal technical condition for R1 down

2.3.4. Asymmetrical R1 upwards : In this strategy, the electrolyser reacts to the grid frequency when the frequency is below 49.9. The power input varies as a function of frequency as:

$$f(x) = \begin{cases} P_{el} = x \cdot P_{max} + \delta \cdot K & \delta < 0 \\ P_{el} = x \cdot P_{max} & \text{Otherwise} \end{cases} \quad (11)$$

Where K is the power frequency characteristic of the electrolyser for a frequency deviation of 0.2 Hz, and $\delta = \text{Freq} - 49.9$. The baseload varies between a technical minimum of 15% and 100%. The power reserve is calculated as:

$$\Delta P = P_{el_{nom}} - P_{el_{min}} \quad (12)$$

As shown in Fig. 11 the net cash flow is always negative. The power-frequency of the electrolyser offering the R1 up product is presented in Fig. 8. The income of 42.9 k€/y from offering primary reserve and 1.3 M€/y from the hydrogen sale are not enough to cover the electricity cost. Therefore, the NPV becomes negative (-41.92 M€/MW/h). However, the NPV

index confirms the profitability of the investment in case of a hydrogen price of 2.8 €/kg. The dynamic response of the electrolyser delivering R1 down and R1 up is shown in Fig. 12. The power input is adjusted either with increasing of frequency (R1 down) or with the frequency drop (R1 up). As shown, the electrolyser mostly operates at a very low capacity which give rise to the poor economic viability.

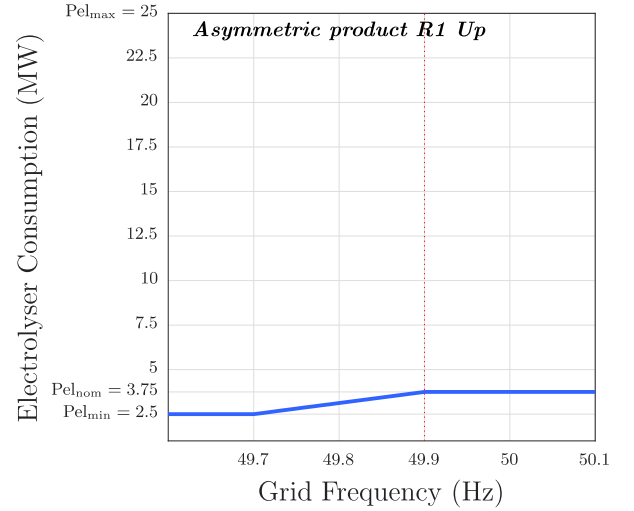


Fig. 10: Power-Frequency chart in the optimal technical condition for R1 up product

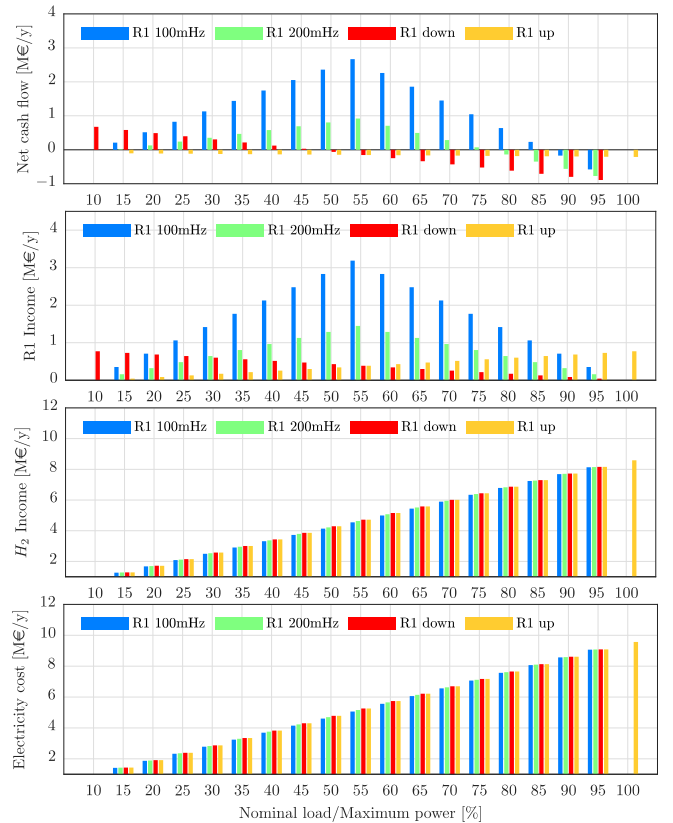


Fig. 11: Economics for the R1 products varying the baseload

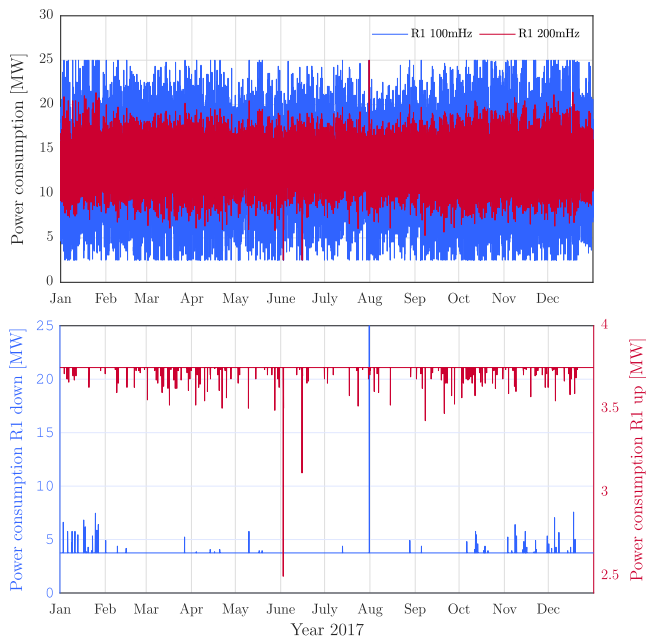


Fig. 12: Comparison of the dynamic power consumption for R1 products

3 Conclusion

This paper has assessed the techno-economic performance of two operational strategies for power-to-hydrogen technology. In the first strategy, the electricity consumption of the electrolyser was modulated according to the predicted electricity price. Later, the electrolyser was operated to participate in the ancillary market, by adjusting the power offtake according to the grid frequency. The results demonstrate that operating the electrolyser to follow the electricity price would not be economically viable, even if a precise prediction of the price was available. This is due to the high investment cost and low hydrogen selling price. It was found that offering the symmetric primary reserve (R1 100mHz) is a valid option to generate additional revenue from ancillary services. The optimal economic strategy is to run the electrolyser at a baseload of 55% of its maximum capacity, while providing the remaining capacity as a power reserve.

The influence of different hydrogen valorisation routes on the foreseen economic framework cannot be determined from this study, and a further investigation needs to be carried out. Further research will also include the impact of partial loading on the electrolyser performance and a shorter time period tendering of ancillary service products.

4 Acknowledgments

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